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Boreal Forest Properties From TanDEM-X Data Using Interferometric Water Cloud Model and Implications for a Bistatic C-Band Mission

Jan I. H. Askne, *Fellow, IEEE*, and Lars M. H. Ulander, *Fellow, IEEE*

***Abstract*—Data from TanDEM-X in single-pass and bistatic interferometric mode together with the interferometric water cloud model (IWCM) can provide estimates of forest height and stem volume (or the related above-ground biomass) of boreal forests with high accuracy. We summarize results from two boreal test sites using two approaches, i.e., 1) based on model calibration using reference *insitu* stands, and 2) based on minimization of a cost function. Both approaches are based on inversion of IWCM, which models the complex coherence and backscattering coefficient of a homogeneous forest layer, which includes gaps where free-space wave propagation is assumed. A digital terrain model of the ground is also needed. IWCM is used to estimate forest height or stem volume, since the two variables are assumed to be related through an allometric equation. A relationship between the fractional area of gaps, the area-fill, and stem volume is also required to enable model inversion. The accuracy of the stem volume estimate in the two sites varies between 16% and 21% for height of ambiguity <100 m. The results clearly show the importance of using summer-time acquisitions. Based on the TanDEM-X results at X-band, C-band data from the ERS-1/ERS-2 tandem mission are revisited to investigate the potential of a future bistatic C-band interferometric mission. Out of nine ERS-1/ERS-2 pairs, only one pair was found to be acquired at summer temperatures, without precipitation and with high coherence. A simulated bistatic phase height is shown to give approximately the same sensitivity to stem volume as TanDEM-X.**

***Index Terms*—Biomass, bistatic SAR interferometry, boreal forest, C-band, X-band.**

I. Introduction

BIOMASS is a key variable in climate models and of high importance for management of natural resources and economic values related to forestry. Various remote sensing techniques are used in order to determine, e.g., above ground biomass, AGB, forest height, and density with sufficient accuracy for the different needs. The ESA BIOMASS mission [1] will use the lowest possible frequency from space, P-band, to achieve high penetration even into tropical forests and in this manner be able to characterize the important AGB components of the forest. On the other hand, satellites sensors such as ICEsat/GLAS [2] are used to characterize height and density of forests by means of lidar. Another promising technique is single pass SAR interferometry using X-band, made possible with the TanDEM-X satellites available, since 2010 [3], [4]. In this article, we will review and extend a technique to model and estimate AGB in boreal forests taking into account the boreal forest structure in terms of height and density. The model used is the interferometric water cloud model, (IWCM) [5], [6], which was first suggested and applied to ERS-1 3 day repeat period and ERS-1/ERS-2 tandem period with a 1 day repeat cycle. The repeat time between the two observations, 1 or 3 days, means that temporal decorrelation had to be taken into account and for good results stable meteorological conditions were necessary, e.g., snow covered ground and subzero temperatures, and a breeze of, e.g., 6–7 m/s or even lower in order for the canopy to be disturbed and cause a temporal decorrelation, resulting in a contrast between canopy and ground. With the launch of TanDEM-X using two satellites simultaneously viewing the same area, the temporal decorrelation is assumed not to affect the results and stable information of the scattering phase center height (simply denoted phase height below) can be obtained, resulting in three-dimensional (3-D) information of the forest.

In order to interpret the remote sensing observations in terms of forest properties, a model involving a number of parameters characterizing the relation between the observations and the forest properties can be used. Physical or empirical relations are used as guiding information.

IWCM has been applied to a number of boreal/hemiboreal field sites with good results for ERS-1/2 when the temporal ground decorrelation is low, and more recently to bistatic TanDEM-X observations together with a DTM. The goal so far has been to apply the model to areas for which accurate field conditions are available, and in this way, determine the potential of the model to produce highly accurate stem volume or AGB and also other forest properties such as height and vegetation density. High accuracy field data give the possibility to investigate the errors associated with the model approximations, since the model is a semiempirical approximation of major scattering properties.

The goal of the present article is to summarize earlier investigations using IWCM in combination with a DTM with results regarding stem volume or AGB, forest height, and horizontal density, including effects of management actions. For

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illustration, one TanDEM-X observation is used from each one of two sites, a boreal site (Krycklan) and a hemiboreal site (Remningstorp). Since IWCM is using allometry for estimating stem volume or AGB, it is investigated how the selected allometry can be supported by an estimate of the maximum stem volume or AGB for the investigated area. The close relation between phase height and the product of H95 and vegetation ratio derived from lidar data is studied and properties of winter relative summer scenes and the optimal conditions using repeat pass or bistatic data are discussed. In order to investigate the potential of a bistatic C-band mission, a set of ERS-1/ERS-2 tandem data is revisited and conclusions drawn.

II. Study Sites and Data

In situ observations from three sites, Remningstorp, Krycklan, and Kättböle will be used in this article. The two first mentioned sites, which are more than 700 km apart, have been used as reference sites for remote sensing of boreal forest many times and the sites have then been described in detail in several publications, e.g., [7]–[17].

Remningstorp (Lat. 58 30° N, Long. 13 40° E) is an estate with 1200 hectares (ha) of productive forest area in the hemiboreal zone. The forest consists mainly of Norway spruce (Picea abies Picea abies (L.) Karst.), Scots pine (Pinus sylvestris Pinus sylvestris L.), and birch (Betula spp.). The test site is fairly flat with elevations ranging from 120 to 145 m above sea level.

Krycklan (Lat. 64 16° N Long. 19 46° E) is a river catchment in northern Sweden and covers approximately 6800 ha, in the boreal zone. The forest consists mainly of Norway spruce (Picea abies Picea abies (L.) Karst.), Scots pine (Pinus sylvestris Pinus sylvestris L.), and birch (Betula spp.). It is a topographic area with ground elevation varying between 145 and 400 m above sea level.

Kättböle, (Lat. 60° N, Long. 17° E) is a forest estate covering 550 ha, located at the southern edge of the boreal zone and characterized by almost flat ground topography. Boreal coniferous species dominate (Scots pine and Norway spruce) even though some broad-leaf trees, mainly birch, are also present.

For Krycklan, 16 TanDEM-X acquisitions from the period June 17, 2011 to Aug. 26, 2014 have been used with HoA varying between 36 and 220 m. The acquisitions correspond to a range of meteorological conditions, i.e., temperatures between -12 °C and 19 °C, and daily precipitation up to 27 mm. For Remningstorp, 18 TanDEM-X acquisitions with HoA varying between 49 and 359 m have been used, acquired between Jun. 4, 2011 to Aug. 2, 2012. Meteorological conditions included temperatures between -4 °C and 24 °C and daily precipitation up to 4 mm. The ERS-1/ERS-2 and TanDEM-X satellite data used in this article have been described in more detail in earlier publications [8], [9], [18]–[21], i.e., the reference data from Kättböle in [6], [18], and [19], from Krycklan in BIOSAR 2008 [22], and from Remningstorp in the BIOSAR 2010 [23].

The number of stands with *in situ* observations used was 42 and 29 for Kättböle and Krycklan, respectively. Airborne Lidar Scanning (ALS) observations were used as reference observations in Krycklan and Remningstorp. In Kättböle, the maximum stem volume of the 42 stands was 334 m^3/ha, in Krycklan 357 m^3/ha of the 29 stands, while the stem volume reaches 569 m^3/ha for the stands in the ALS area. In Remningstorp, we have studied 202 stands larger than 1 ha with ALS coverage and stem volumes up to 519. By including smaller areas ($>$ 0.01 ha), the number of stands increases to 454 and the maximum stem volume reaches 617 m^3/ha.

The dataset includes seasonal variations covering mainly summer conditions, but also snow melt, frozen conditions, and high precipitation. However, conditions outside summer conditions are relatively few.

A. Examples of Forest Properties

Important variables used in forestry are basal area (BA, i.e., average cross-sectional area at breast height of trees per hectare), Lorey's height (hL, i.e., average tree height weighted by the basal area), stem volume (V, i.e., average volume of trees per hectare, including bark but excluding stumps and branches), and above-ground biomass (AGB, i.e., average above-ground dry biomass per hectare). Estimation of these variables from field measurements is costly and remote sensing techniques are becoming cost-effective alternatives, e.g., using ALS. Vegetation ratio and H95 are common parameters from ALS. Vegetation ratio is defined as the fraction of returned lidar pulses reflected from a point located higher than a threshold height of 1.37 m above ground. H95 is defined as the 95 percentile height of the returned lidar pulses reflected above the same threshold height. As will be described below, IWCM uses two other parameters, i.e., forest height and area-fill, as will be described further below. Area-fill is defined as the fraction covered by vegetation, i.e., which affects the electromagnetic wave by attenuation and scattering. In the following, we will use H95 or hL as proxy for forest height h and vegetation ratio corrected by a factor κ as proxy for area-fill.

For Remningstorp with relatively high stem volume values, we find a slightly nonlinear relation between BA and stem volume, see Fig. 1. The vegetation ratio is reaching a plateau value at higher stem volumes and the vegetation ratio times H95 is slightly nonlinear.

The dotted lines in Fig. 1 are $BA(V) = (0.65V)^{0.67}$, and

$$h\left(\mathrm{V}\right) = \left(2.44\mathrm{V}\right)^{0.46} \tag{1}$$

$$\eta\left(\mathrm{V}\right) = 0.9\left(1 - e^{-0.01\mathrm{V}}\right) \tag{2}$$

where h(V) and η(V) are used allometric relations in the analysis of IWCM below. The units of BA(V), h(V), and V are m^2/ha, m, and m^3/ha, respectively. η(V) is a fraction and therefore unitless. h(V) is based on NFI (National Forest Inventory in Sweden) observations from large parts of Sweden and has been used since [5], [6] for InSAR, interpretation from sites in Sweden and Finland. h(V) is also shown in the dotted line the upper right figure of Fig. 1. η(V) is an allometric expression for the area-fill introduced more recently [20]. The dotted line in the lower right figure is the interferometric phase height determined by IWCM from TanDEM-X observations from Jun. 4, 2011,

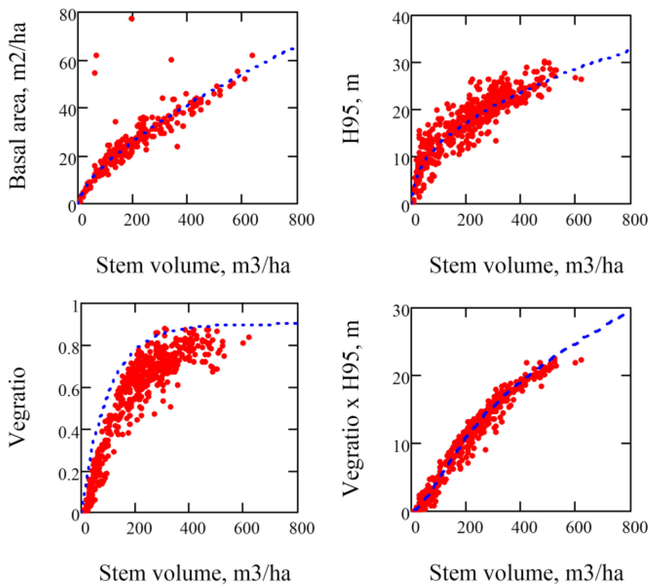

Fig. 1. ALS based estimates from Remningstorp of 454 areas ≥ 0.01 ha. For explanation of dotted lines, see text below.

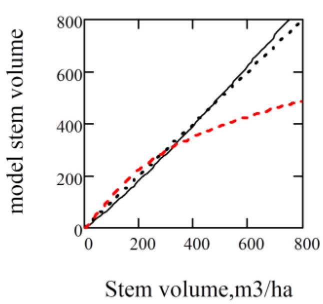

Fig. 2. Two stem volume models are shown. 1) Model based on basal area and height [0.4 BA(V)h(V)], shown in black solid line, 2) Model based on phase height as proportional to ρh(V)η(V)/κ, to be discussed below, shown as red dashed line. The phase height model is based on TanDEM-X observations of Remningstorp Jun. 4, 2011.

illustrating that the phase height varies with stem volume in the same manner as the vegetation ratio times the height.

The stem volume, V, can be expressed as f BA h, where f is a tree form factor [24], and BA is the basal area. f BA h is illustrated in Fig. 2 as function of stem volume as well as ρh(V)η(V)/κ, with $\rho = 20$ m^2/ha and $\kappa = 1.2$, which will be shown to be a good approximation of phase height, Ph, for the observations studied. From Fig. 2, we see that f BA h is a good measure of stem volume but ρh(V)η(V)/κ or ρPh only is proportional up to $\approx$350 m^3/ha, cf. [25]

III. Interferometric Water Cloud Model

A. The Model

A general view of X- and C-band microwave interaction with a forest is that the penetration of the vegetation is limited or even negligible and that the dominating backscatter is caused by twigs and small branches located in the upper part of the canopy and with sizes of the order of the wavelength. However, microwaves can propagate without significant loss through gaps in the canopy and reach lower levels and even the ground level. If the forest is not too dense, which is typical for boreal forest, we have gaps of all sizes within and in between the trees. The gaps or openings do not need to be large, typically the size of a few wavelengths in order for the radiation to propagate through relatively unperturbed. This is known since long and was illustrated recently in the case of L-band with a wire grid above a dielectric surface [26]. We therefore introduce in the model, describing the interaction between microwaves and forest, a measure of the fractional area of ground reached by the microwave radiation directly in line of sight from the satellites, and the backscatter from different layers of the dense (no gaps down to ground) forest fraction plus the attenuated part from the ground. The latter fraction of the forest is denoted the area-fill, η. An important empirical result in [21] is that the phase height is observed to be proportional to H95 times the vegetation ratio. This illustrates the importance of the forest density for the model analysis.

In IWCM, the backscatter is expressed as the incoherent summation of the direct backscattering coefficient of the ground, σ^0_{gr}, plus the backscattering coefficient of the vegetation layer, σ^0_{veg}, including parts transmitted through and attenuated by the vegetation. Similarly, the complex coherence, $\hat{\gamma}$, is expressed as an incoherent sum of the contribution from the ground directly and from the vegetation layer including the volume decorrelation, $\tilde{\gamma}_{\mathrm{vol}}$, related to the vegetation and caused by the decorrelation due to the phase shifts between the different height layers as seen from the satellites. γ_{veg} and γ_{gr} are terms describing system decorrelation and any extra decorrelation, respectively.

IWCM has been described in several papers, most recently in [21]. The basic expressions for backscattering coefficient and complex coherence are included for completeness.

$$\begin{aligned}\sigma^0_{\mathrm{for}} &= (1-\eta)\ \sigma^0_{\mathrm{gr}} + \eta\ \left[\sigma^0_{\mathrm{gr}} e^{-\alpha h} + \sigma^0_{\mathrm{veg}}\left(1-e^{-\alpha h}\right)\right] \\ &= \sigma^0_{\mathrm{gr}}\ e^{-\alpha_{\mathrm{tot}} h} + \sigma^0_{\mathrm{veg}}\left(1-e^{-\alpha_{\mathrm{tot}} h}\right)\end{aligned} \tag{3}$$

$$\hat{\gamma} = \frac{\gamma_{\mathrm{veg}}\tilde{\gamma}_{\mathrm{vol}} + \gamma_{\mathrm{gr}} m}{1+m} \text{ and } \tilde{\gamma}_{\mathrm{vol}} = \frac{\int_0^h e^{-\alpha(h-z')}\cdot e^{-j k_z z'}\mathrm{d}z'}{\int_0^h e^{-\alpha(h-z')}\mathrm{d}z'} \tag{4}$$

with

$$e^{-\alpha_{\mathrm{tot}} h} = 1-\eta\left(1-e^{-\alpha h}\right) \text{ and } m = \frac{\sigma^0_{\mathrm{gr}}}{\sigma^0_{\mathrm{veg}}}\,\frac{\frac{1-\eta}{\eta}+e^{-\alpha h}}{1-e^{-\alpha h}}. \tag{5}$$

$k_z = 2\pi$/HoA. One possibility to introduce a stem volume dependence is to assume exp(-α_{tot} h) = exp(-βV) [27], which will be discussed below.

The phase of $\hat{\gamma}$ determines the phase height, and the amplitude of $\hat{\gamma}$ the coherence. γ_{veg} and γ_{gr} represent temporal and system related decorrelation terms, respectively, while m represents the ground to volume influence. α, Np/m, is the two-way vertical attenuation of the dense forest. η and h represent the horizontal, respectively, the vertical variation of the stands and are assumed to vary with stem volume or AGB, which is assumed to be related to stem volume by a constant typical for the tree mixture.

The ALS-based vegetation ratio is a proxy for area-fill η as mentioned above. Due to the longer wavelengths and different incidence angle of the microwaves compared to ALS, η is assumed to reach higher values than the vegetation ratio by a factor κ. Lorey's height hL or the ALS-based H95 are used as proxy for forest height *h*.

To determine the parameters involved in the model, we may use reference areas with known properties cf. [8]. Another alternative is to use allometric relations *h*(V) and η(V), derived from field measurements representative for the forest in question [9], [20], [21], [28], [29]. Our primary goal is to estimate stem volume or AGB and we assume that η and *h* can be expressed as allometric functions of stem volume. In the case of *h*(V) such an expression can be determined from, NFI, plots, while η(V) has to be estimated from lidar measurements. The expressions can be assumed to be related to the type of forest and its management. With satellite lidar instruments such as ICESat GLAS, see e.g., [30], [31], we may find relations between *h* and η although the type of measurements are different, in particular, the resolution of the sensors.

B. Fitting the Model to Observations

Here, we will only give a principal description on how to use the model to estimate forest parameters. For a mathematical description, see [9] for the case HoA < 100 m and $\gamma_{\rm veg} = \gamma_{\rm gr} = \gamma_{\rm sys}$. The model includes the forest variables stem volume V and the four model parameters, $\sigma^o_{\rm gr}, \sigma^o_{\rm veg},\ \gamma_{\rm sys},\ \text{and}\ \alpha$. The observation is also characterized by the known height of ambiguity, HoA.

We require that the model phase height should be equal to the observed phase height. From this relation, we have an indirect expression for the stem volumes of the observed forest stands expressed in the phase height according to the model, the parameters, and the observed phase height. Equations (3) and (4) define the models for coherence and backscatter. The relative RMSE between the model values and observed values for coherence and backscatter, respectively, are denoted by $\text{RMSE}_{\rm coh}$ and RMSE_{σ}. We define a cost function as the combined RMSE according to

$$\text{RMSE}^{-1} = \text{RMSE}^{-1}_{\rm coh}\ + \text{RMSE}^{-1}_{\sigma}. \tag{6}$$

RMSE, which is a function of the model parameters, is now minimized starting from initial guess values. For details, see [9]. When HoA $>$100 m, we may need to assume $\gamma_{\rm gr} \neq \gamma_{\rm veg}$ and the minimization is more complex, see [20].

Minimization of RMSE leads to expressions for the model parameters, $\sigma^o_{\rm gr}$, $\sigma^o_{\rm veg}$, α, $\gamma_{\rm sys}$, which together with the observed phase heights result in estimates of stem volume of each forest stand. The forest height, *h*(V), and the area-fill η(V) for the stands are determined by the allometric relations (1) and (2).

An alternative manner for solution is given in [28] using a nonlinear least-squares optimization by including a random error between the observed and modeled phase height.

As an extension of the solution, denoted IWCM2 and IWCM can be expressed as functions of *h* and η and the estimated model parameters when HoA < 100 m. By equating the model coherence and phase height to the observations, see [21] stand values for *h* and η are determined. Since $\gamma_{\rm sys}$ is determined as a mean parameter for all stands and the exact value for a specific stand is unknown the results for *h* and η are uncertain for stands with phase height less than ≈ 5 m and were excluded.

A computer program in Mathcad 15 for acquisitions with HoA < 100 m, can be obtained from the first author. Mathcad is a commercial calculation tool in which equations are created and manipulated in the same graphical format in which they are presented. Any other engineering math software program can be used.

IV. Model Properties

A. Dependence of Phase Height on Forest Properties

An important result in [21] was that the phase height can be approximately equal to H95 times vegetation ratio (denoted Vegratio in figures) for the summer observations, illustrated when HoA < 100 m. This result illustrates the importance of vegetation density to understand phase height. The phase height is expected to be obtained as the sum from the gap area, 1-η, from which we have zero phase height, and from the dense forest area, η, for which the phase height is determined from (4) and (5) with $\eta = 1$. The contribution from ground is small when exp(-αh) $<< 1$ and then the phase height is determined by the volume decorrelation to h – 1/α if also 2π/(α HoA) $<<$1 [8], [18]. This means that the phase height Ph can be approximated as

$$Ph\,(V) \approx \eta\,(V)\,[h\,(V)\ - 1/a]. \tag{7}$$

If 2π/(αHoA) is not too small, we may change α to $\alpha_{\rm eff}$ [8] by comparison with the full expression for Ph(V). The approximation is illustrated in Fig. 3.

Treuhaft *et al.* [32] introduced the mean canopy height, MCH

$$\text{MCH}\ (\alpha, V) = \frac{\int_0^{h(V)} z e^{\alpha} dz}{\int_0^{h(V)} e^{\alpha} dz}\ = \frac{h\,(V) - \frac{1}{\alpha}\left(1 - e^{-\alpha h(V)}\right)}{1 - e^{-\alpha h(V)}} \tag{8}$$

which is a good approximation for the phase height when the complex coherence is determined by $\gamma_{\rm vol}$. When exp(-αh) $<<$ 1 MCH tends to h – 1/α. With $\alpha = \alpha_{\rm eff}$ there is for Krycklan and Remningstorp in practice no difference between the expressions and the phase height tends to η(V)MCH($\alpha_{\rm eff}$,V).

B. Sensitivity of Allometry for Stem Volume or AGB

Height is the primary variable for which the bistatic InSAR observations are sensitive, but since stem volume or AGB is the most important forest property the relation to stem volume is introduced through the allometry *h*(V). The allometric relation is then of major importance for the accuracy of stem volume estimation. In addition, we require a model for the area-fill η(V). Based on the empirical fact that phase height is directly proportional to H95 times vegetation ratio, or by *h*(V)η(V)/κ in model expressions, we came to the conclusion that $\kappa \approx 1.2$ [21] assuming *h*(V) $=$ (2.44 V)$^{0.46}$. Now, we will investigate the model dependence on *h*(V) by comparing the earlier case

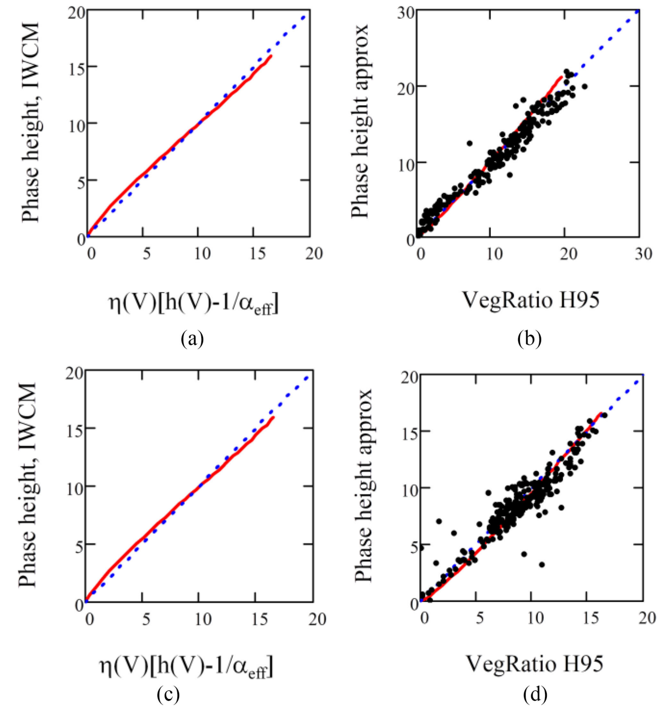

Fig. 3. (a) and (c) Illustrating the relation between the phase height according to IWCM and its approximate relation η(V)[h(V)-1/α_{eff}] (red line) and (b) and (d) approximate phase height versus h(V) η(V)/κ with $\kappa = 1.2$ and observations. The upper figures are for Remningstorp 2011-06-04 with $2\pi/(\alpha\mathrm{HOA}) = 0.48$, $\alpha = 0.27$ Np/m and $\alpha_{\mathrm{eff}} = 0.38$ Np/m, and the lower figures are for Krycklan 2011-06-17 with $2\pi/\alpha\mathrm{HOA} = 0.85$, $\alpha = 0.14$ Np/m and $\alpha_{\mathrm{eff}} = 0.30$ Np/m.

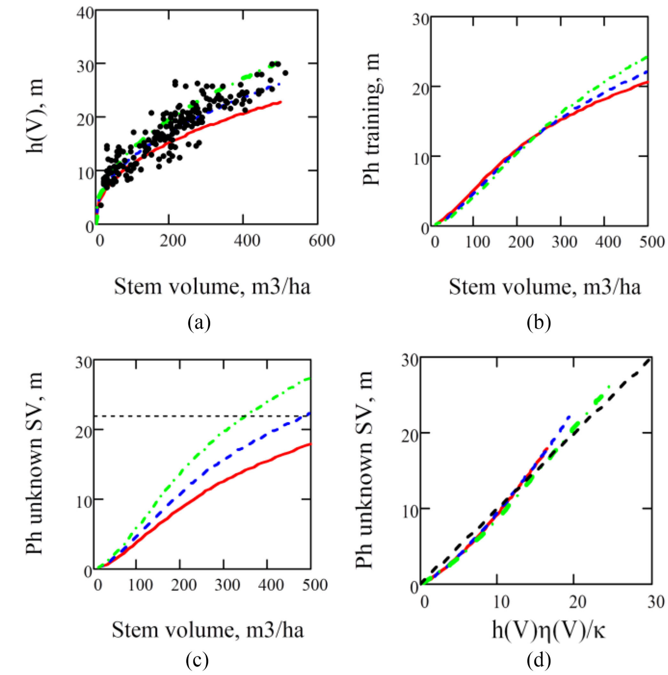

Fig. 4. (a) Illustrating the different allometric models for h(V) together with ALS observations; (b) Illustrating the phase height estimated with the different h(V) using all stands with known ALS-based stem volumes for training; (c) Illustrating the phase height estimated with the different h(V) assuming unknown stem volumes, and (d) comparing the phase height estimated with the different h(V) assuming unknown stem volumes and compared with h(V) η(V)/κ with $\kappa = 1.24$, 1.20, and 1.06, respectively. The exponential 0.44 corresponds to red solid line, 0.46 to dashed blue line and 0.48 to dashed-dotted green line.

with the assumption that $h(\mathrm{V}) = (2.44\ \mathrm{V})^{0.44}$ or $(2.44\ \mathrm{V})^{0.48}$. The result derived from TanDEM-X observations from Jun. 17, 2011 from Remningstorp is illustrated in Fig. 4.

By using known stem volume these act as constraints on the solution, since we know, for example, the highest stem volume (511.7 m^3/ha) corresponds to a phase height 21.9 m. If we can estimate the highest stem volume for the area investigated, e.g., from NFI-plots to ≈ 500 m^3/ha, we may plot the observations together with the model solutions for stem volumes up to 500 m^3/ha, see Fig. 5. The end point of the model line corresponds to 500 m^3/ha and is marked with a dot. If we connect this dot to the origin of the coherence diagram, we see that all the phase heights of the observations are included for the blue dashed case and this is the case corresponding to the best fit of the three h(V) allometries. The same is seen in the backscatter diagram.

The coefficient of determination, $r2$, between estimated stem volumes and *in situ* stem volumes are in all cases 0.92, but in the first case, we over estimate and in the last case, we under estimate stem volume, cf. Fig. 4(c) resulting in relative RMSE values for stem volume in the three cases of 41.4%, 16.6%, and 32.8%, indicating the need for accuracy in the h(V) allometry, but also the possibility to control the used allometry by means of an estimate of the highest stem volume values in the area as a calibration point together with the TanDEM-X observations.

In [21], it was shown how the allometric properties of η(V) can be checked.

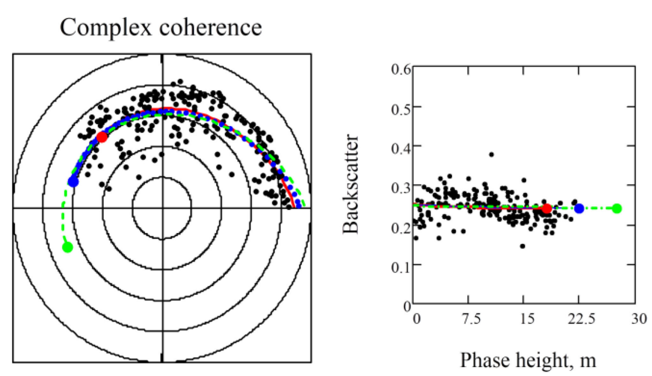

Fig. 5. Illustrating the observations together with the model solved with the allometries, notations as in Fig. 4.

V. Experience From TanDEM-X Observations

Remningstorp and Krycklan are test sites in Sweden in the hemiboreal and the boreal area, respectively, with extensive field measurements [22] [23]. With the *in situ* data available, a goal has been to test the properties and the estimation accuracy of IWCM in [8], [9], [20], [21], [28], and [29]. Many other studies have also been carried out based on these campaigns giving possibility to compare different techniques and different models, see the above references related to the sites.

The major goal has been to estimate stem volume or AGB. Stem volume is the main forest variable of interest in

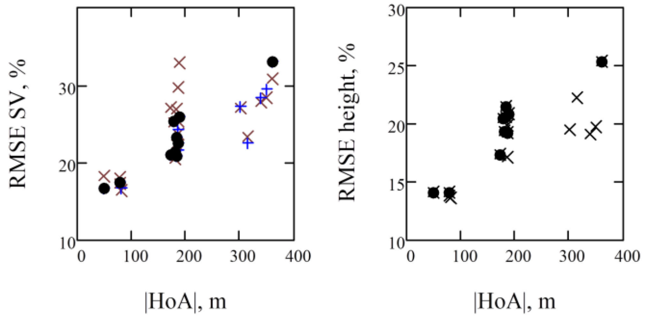

Fig. 6. Relative RMSE for stem volume and forest height for acquisitions in Remningstorp using the βV-approach and training stands (+),without rain (•) and using allometry without training stands (x). Part of the results is from [20].

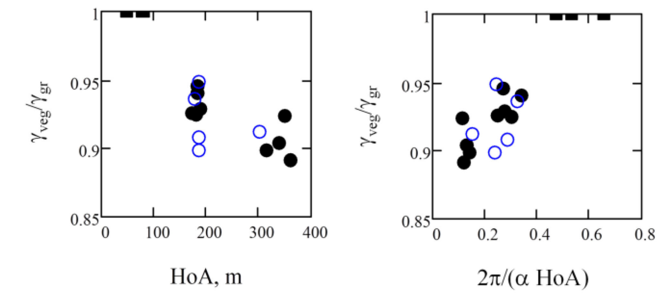

Fig. 7. γ_{veg}/γ_{gr} estimates for measurements with HoA $<$ 100 m, ■; those with HoA $>$ 100 m and a wind speed $<$ 3 m/s, •; and those with wind speed $>$3 m/s, o.

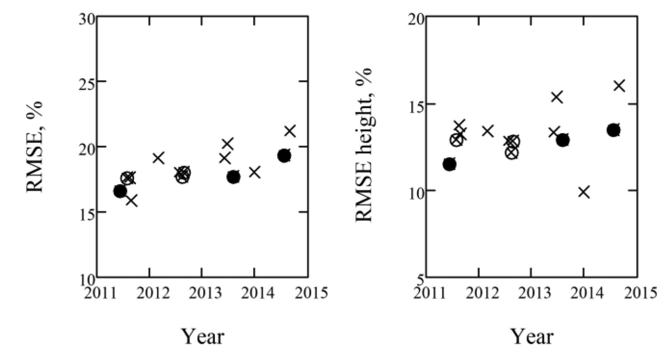

Fig. 8. RMSE for stem volume and forest height versus BIOSAR 2008 in situ measurements in Krycklan using allometry without training stands. Three measurements not affected by precipitation are marked by •,while additionally three measurements are affected by limited precipitation and marked by o in addition to x. Results partly from [9].

characterizing the economic value of a forest. For this reason, the original goal of IWCM was focused on estimating stem volume.

A. Obtained Results From Remningstorp

For stem volume or AGB, the relative RMSE is estimated to be in the range 17% $<$ RMSE $<$ 19% for HoA $<$ 100 m and $<$ 33% for HoA $<$ 400 m. For a multitemporal combination of all the acquisition the RMSE for stem volume or AGB was obtained to 16% in [8] using the exp(-βV)-approach combined with training stands, and 17% using the allometry approach without training stands in a manual iterative manner [20]. The results with the two methods are approximately the same. The relation between height and stem volume is determined by h(V) and RMSE for height and stem volume or AGB are illustrated in Fig. 6. The RMSE is expected to increase approximately linearly with HoA, since the phase height is of major importance for height and then also for stem volume estimation, but RMSE is also dependent on meteorological conditions, in particular rain.

Based on ALS measurements from 2010 and 2014, the forest change of 3 x 12 plots of 0.28 ha each and with different management actions plus 12 stands with natural growth were investigated. The latter stands resulted in a height growth of 2.7%/year with TanDEM-X/IWCM versus a 2.1%/year growth with ALS, and a biomass growth of 4.3%/year versus 4.2%/year from ALS [21]. The stands with different management actions, representing precommercial thinning, commercial thinning, and clear-cutting, resulted in much insight into the sensitivity of IWCM. A principal diagram over height versus area-fill for the different types of management actions as an alternative to ALS characterization of the different stand actions was given.

B. Decorrelation Effects

Observations from Remningstorp include acquisitions with HoA up to 358 m [8], [20]. The vegetation and ground decorrelation were included separately in the solution approach, cf (4). γ_{gr} and γ_{veg} were found to be slightly different, see Fig. 7, with a ratio decreasing with HoA, i.e., increasing with the normal baseline between the satellites or with $2\pi/(\alpha\text{HoA})$ i.e., the phase shift over the penetration depth. The effect does not seem to be related to wind decorrelation (wind speeds up to 6 m/s) and not to the along track distance, ATB (up to 267 m). Generally temporal decorrelation is not expected in the bistatic InSAR case.

When HoA is large the volume decorrelation is small and the coherence is close to γ_{sys}. However, in order to obtain agreement with the observed coherence $\gamma_{veg} < \gamma_{gr} = \gamma_{sys}$ have to be included in the model. This complicates the estimation procedure since one more unknown parameter is included, see [8] and [20]. It should be noted that the acquisitions with HoA $>$ 100 m are from another orbit with another angle of incidence than those with HoA $<$ 100 m. which also means another noise equivalent sigma zero. This will be a topic for future work.

C. Obtained Results From Krycklan

For stem volume or AGB, the relative RMSE is estimated to be in the range 16% $<$ RMSE $<$ 21% for HOA $<$ 63 m, and for forest height 10% $<$ RMSE $<$ 16%, see Fig. 8. In the Krycklan case, HoA for all the summer acquisitions were in the range 36–80 m and $\gamma_{veg} = \gamma_{gr} = \gamma_{sys}$ was assumed. In Fig. 8, the RMSE summer values are illustrated as function of time in order to illustrate that the RMSE values are degraded by growth effects relative the 2008 reference values. Acquisitions when there is no precipitation show a consistent growth.

Using the IWCM2 approach, the RMSE for heights with phase heights above 5 m varied between 6% and 8% but for one acquisition it was 11%.

The 12 summer time observations from 2011 to 2014 were used to determine AGB growth. Summer time acquisitions are preferred due to the larger span of phase heights and the associated higher sensitivity to stem volume. The maximum growth rate of AGB, was 4.0 Mg/ha/yr with a mean rate of 1.9 Mg/ha/yr for 27 stands, varying initially between 23 to 183 Mg/ha.

D. On Optimal Conditions for Stem Volume or AGB Estimation

From single baseline bistatic TanDEM-X data combined with a DTM, we obtain phase height, coherence, and backscatter as observables, and an important question is which conditions are optimal for estimation of forest properties by means of IWCM. A wide range of seasonal variations in Krycklan has been investigated in [9] and [28]. The largest difference of the observables is between summer and winter conditions due to the freezing water in the canopy. The acquisition with lowest temperature studied here, cf. [9], is from Krycklan Feb. 25, 2012 with a temperature of -9 °C and a 1 m snow layer. In Fig. 9, the observations from Jun. 26, 2011 and Feb. 25, 2012 are illustrated as function of stem volume together with IWCM model results. The observations from Feb. 25, 2012 have also been analyzed with the DTM corrected by 1 m due to a likely dense snow or ice layer related to the temperature history with temperatures around zero on Feb. 20, 2012. For comparison, the acquisition from Jun. 17, 2011 is also illustrated. In Krycklan, AGB is estimated by ALS and in IWCM AGB is estimated as 0.512 Mg/m^3 times the estimated stem volume.

Typical for frozen conditions is a low canopy attenuation, which also means that the ground contribution to coherence is more important winter than summer. More stable properties associated with (a snow covered) ground result in smaller variability in coherence of the observations. The phase height, however, is formed in the canopy with variable properties. It has been noted that TanDEM-X coherence shows a high sensitivity to forest height in winter cf. [33], [34]. In Fig. 9, we note the small variability of coherence with the stem volume. We also see the low range of phase height values during winter ($<$10.6 m Feb. 25, 2012 relative the DTM compared to $<$16.5 m Jun. 17, 2011). This can be compared to the range of coherence values, $\approx$ 0.33, summer as well as winter. The phase height range is significantly higher during summer due to the higher attenuation and lower penetration into the canopy. The larger phase height range in summer improves the estimation of stem volume and AGB.

From the IWCM analysis, we obtain an RMSE for AGB estimation of 26.9% for the winter case without the 1 m correction of the DTM and 19.3% with the correction. The IWCM parameters in the DTM corrected case are similar to those obtained when reference AGB are used, which strengthens the hypothesis of an ice layer in the snow. This result illustrates the problem of using phase height during the winter due to the uncertainty of the effects related to a possible snow or ice layer. For the summer acquisition, the AGB estimation is characterized by RMSE $=$ 16.7%.

The above results underline the importance of phase height relative coherence for summer acquisitions and a question is to what extent phase height varies over the seasons. Due to the close relation to the product HV $=$ H95•Vegetation ratio as determined by ALS 2008 (Krycklan) and 2010 (Remningstorp), we investigate the variation of the coefficient of determination and root mean squared error, r2(Ph,HV), and RMSE(Ph,HV). We find that due to growth r2(Ph,HV) decreases and RMSE(Ph,HV) increases with time from the first TanDEM-X summer measurements. For the latter cases, we obtain $r2 \approx 0.95$ and RMSE $\approx$ 10% for HoA around 50 m. The results worsen for increased HoA due to the decreasing height sensitivity, which also worsens the result for stem volume and AGB estimation. The values worsen for conditions with subzero temperatures and a snow layer in Krycklan, and in Remningstorp for temperatures close to 0 °C with precipitation as well as a snow layer. We also note a clear relationship between a decrease in r2(Ph,HV) and an increase in RMSE(Ph,HV) with an increase in the RMSE between the AGB estimated by IWCM and the corresponding reference values based on *in situ* data.

We conclude that for bistatic InSAR using a DTM, the optimal conditions to estimate stem volume or AGB are mainly due to a large range of phase height values as obtained during summer time with less penetration into the canopy combined with HoA $<$ 80–100 m. Cases with precipitation should be avoided due

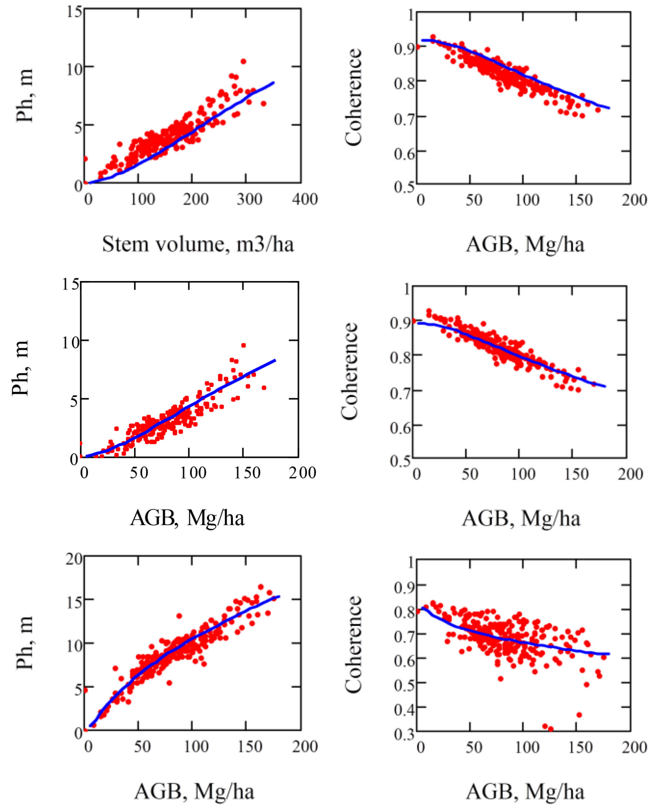

Fig. 9. Illustrating TanDEM-X data from Krycklan, in the upper row from Feb. 25, 2012, in the middle row from Feb. 25, 2012 with the phase height decreased by one meter and in the lower row from Jun. 17, 2011. The solid blue lines represent the IWCM model solution on respective dataset.

to effects primarily on the backscatter, but also on complex coherence.

VI. Prospects of Bistatic C-Band InSAR Observations

The introduction of IWCM was originally associated with the 3-day repeat data from the C-band ERS-1 satellite and later the ERS-1/ERS-2 1-day tandem repeat pass data. Due to the time interval between the observations temporal decorrelation of ground as well as canopy had to be taken into account in the original version of IWCM, [5], [6], [35]. The observed phase height was in addition corrupted by different phase shifts from the atmosphere at the two acquisitions [19] and only coherence and backscatter were used for estimating stem volume. The model parameters were obtained by means of the exp(-βV)-approach and using training stands together with an assumption regarding the attenuation at C-band.

A bistatic configuration at C-band, cf [36] would have eliminated the temporal decorrelation and made accurate phase height measurements possible. With the information of the IWCM parameters from the most accurate ERS-1/ERS-2 observations, it may be possible to investigate the potential of a bistatic C-band mission.

Nine C-band observations from Kättböle, 35 km NW Uppsala, studied in [6], [18], and [19] were previously solved with the exp(-βV) approach, and will now be investigated with the method in [9] and [20] using the same allometry as above. In order to determine the IWCM parameters with as high accuracy as possible, the estimation will be done using the known *in situ* stem volumes. Due to the temporal decorrelation related to the 1 day time difference between the acquisitions the associated terms, $\gamma_{\rm gr}$ and $\gamma_{\rm veg}$ (including the effect of $\gamma_{\rm sys}$) were included in the model analysis. The IWCM parameters are illustrated in Fig. 10 as function of temperature.

From [6], [18], and [19], we note that four of the nine pairs are acquired during stable weather conditions, and five under changing weather. If stem volume is determined from ERS-1/ERS-2 coherence the optimal conditions are for high ground coherence as in winter cases with snow covered ground combined with a relatively low vegetation coherence related to wind effects. In this case, we have a range of coherence values giving sensitivity to stem volume. For bistatic SAR, the optimal conditions are different and a large range of phase height values during summer time with less penetration into the canopy are optimal combined with HoA $<$ 100 m.

To simulate bistatic conditions, we have to look at those acquired under stable weather conditions and we will only consider summer conditions, due to the higher range of phase height values, and in particular that from Aug. 20/21, 1995 with temperature 16 °C, $\gamma_{\rm gr} = 0.82$, and $\gamma_{\rm veg} = 0.41$, and HoA $=$ 119 m, indicating a high ground coherence and a relatively high vegetation coherence. Only this acquisition as well as that from Jul. 20/21, 1995 has summer temperatures of at least 16 °C, but for the latter pair, we had rain at one of the acquisitions. The simulated phase height for a bistatic C-band mission ($\gamma_{\rm veg} = \gamma_{\rm gr}$) corresponding to the Aug. 20/21, 1995 pair is illustrated in Fig. 11 together with h(V)η(V)/κC, where κC is adjusted to 1.10

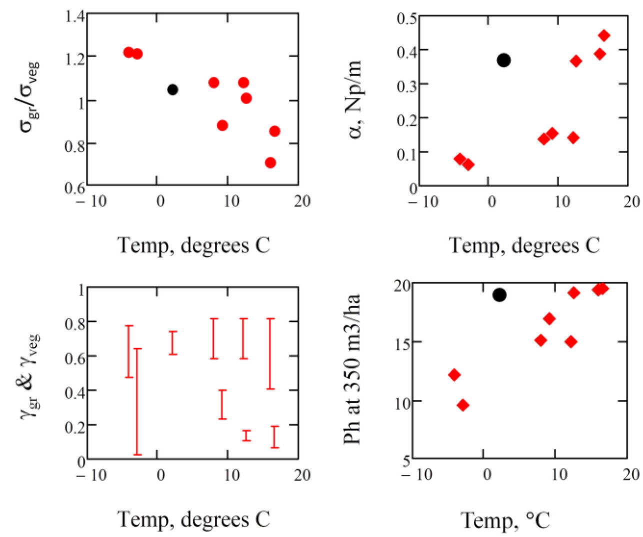

Fig. 10. Illustrating ERS-1/ERS-2 tandem data as function of the mean temperature of the two acquisitions. The acquisition at 2.1 °C is marked since the temperature is the mean of $+4.1°$ and $0°$ combined with 3 mm precipitation i.e., risk for thawing and freezing. $\gamma_{\rm veg}$ and $\gamma_{\rm gr}$ are marked with a connecting line. The simulated phase heights for bistatic observations ($\gamma_{\rm veg} = \gamma_{\rm gr}$) at 350 m^3/ha are illustrated in the lower right corner.

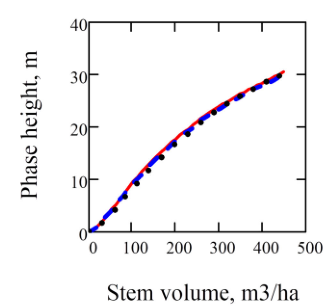

Fig. 11. Illustrating the simulated phase height for bistatic C-band InSAR based on ERS-1/2 observations from 1995-08-20/21. The solid line is the phase heights, the dashed black lines is h(V)η(V)/κC with $\kappa C = 1.10$.

for agreement between the two expressions. A κC value of 1.1 at *C*-band is smaller than 1.2 at *X*-band and the two-way attenuation of 0.39 Np/m is larger than the *X*-band value of 0.15 Np/m typical for Krycklan and 0.26 for Remningstorp. If the attenuation in the dense forest is dominated by gaps down to different levels, the *X*-band radiation with smaller wavelength than *C*-band would propagate to lower levels, which would correspond to a smaller attenuation.

The result indicates that the sensitivity for stem volume or AGB would be similar for a *C*-band bistatic mission as for TanDEM-X, not taking into account other *X*- and *C*-band differences such as, e.g., resolution. However, it should also be stressed that the results are only indicative since the comparison with observations suffering from a one day interval and associated temporal decorrelation is problematic, but it is the only information available.

VII. Discussion and Conclusion

A. Some Properties of IWCM

This article is focused on IWCM observations from single-baseline bistatic VV-polarization TanDEM-X and lidar-based DTM. It also includes IWCM analysis based on *C*-band ERS data and discusses properties of a possible future bistatic *C*-band mission. Stem volume or AGB has been in focus in this article due to its importance as an essential climate variable, but estimation of height, density, growth, and management actions using IWCM have also been described and summarized from [8], [9], [20], [21], [28], [29].

Although bistatic InSAR is primarily sensitive to the forest height, IWCM is based on using the allometry for stem volume or AGB inherent in the model. The equations are then adjusted to the observations over an area covering a range of forest properties and IWCM parameters and stem volume or AGB are estimated. The IWCM parameters for the area can also be used to estimate height and density. The extinction coefficient estimated with IWCM is representative of a dense forest.

IWCM is using the information from backscatter as well as complex coherence. The extra information from backscatter is expected to increase the accuracy but can create a problem at times of heavy rain, which seems to affect backscatter more than phase height and coherence.

DTM information can be obtained from lidar-investigations as in this article, or possibly from the BIOMASS mission in the future [1]. In [37], a possibility to determine the ground level from TanDEM-X data is studied.

B. Other Model Approaches

Other model approaches to analyze bistatic TanDEM-X data in the boreal or hemiboreal region without the use of known reference data for training the model parameters are the Random Volume over Ground, RVoG, [38]–[41] and the Two Level Model, TLM [42]–[44].

RVoG is based on estimates of height and extinction, and by means of allometry the height can be related to stem volume or AGB [33], [45], [46]. TLM is used to estimate height and density properties and, by training using NFI plots, stem volume or AGB estimates can be obtained [47].

Some studies of particular interest in relation to the present study with focus on the specific test sites Krycklan and Remningstorp are [4], [46]. Kugler *et al.* [4] studied the potential of RVoG for forest height estimation of TanDM-X acquisitions in different sites including Krycklan. They used a DTM for phase height estimation using single-pol and dual-pol inversion, then without a DTM, and obtained an RMSE of 1.6 and 2.0 m, respectively. The inversion was achieved by assuming a zero ground-to-volume amplitude ratio for at least one polarization independent of height. Caicoya *et al.* [33] studied the potential of RVoG in single polarization TanDEM-X without the use of DTM, using one or two baselines in Remningstorp and Krycklan. Then only coherence information is used and fixed extinction and ground-to-volume parameters are estimated from experience. From height AGB was estimated, resulting in a classification of AGB in four classes. An interesting result is that winter acquisitions are favored for stem volume estimation in this article based on coherence analysis. Investigations of TanDEM-X coherence from observations of a hemiboreal site are illustrated in [34]. The observations illustrated the small variability of coherence during winter time.

The BIOSAR 2008 and BIOSAR 2010 *in situ* data from Remningstorp and/or Krycklan have been used in many remote sensing investigations and can then be compared with results derived by TanDEM-X results in this article, e.g., PolInSAR using RVoG for *L*- and/or *P*-band, e.g., [12], [17] or only *L*-band [48] or the influence of forest density on forest height using RVoG [11] or vertical structure [49] using RVoG.

C. Conclusion

A major goal in forest remote sensing is to determine stem volume or AGB, since AGB is an essential climate variable [50], and stem volume is the important property of interest in characterizing the economic value of a forest. Stem volume and AGB can be approximately related by means of a constant depending on tree species and composition. Note that remote sensing techniques are not directly sensitive to stem volume (or AGB) but indirectly in the form of sensitivity to, e.g., forest height and canopy gaps, and the measured properties must be related to stem volume (or AGB) by empirical relations. In IWCM two such relations are used, c.f. 1) for the height to stem volume relation and 2) for the area-fill to stem volume relation, which both are given in terms of allometric equations. The former is known with good accuracy for some forest types, e.g., managed boreal forests, but less accurate for, e.g., unmanaged forests and tropical forests. This is a limitation of the inversion which future research should investigate and study mitigation techniques. We showed one example that suggests progress in this direction, i.e., the correctness of the allometric relation by using independent knowledge of the maximum stem volume in the area. The allometric equation for the area-fill has previously been shown [21] to be related to the vegetation ratio.

The RMSE for stem volume given in this article for the two sites 700 km apart are in the range of 15–20% as long as the height of ambiguity is less than 100 m. Estimates of height and density are more directly related to the measurements than stem volume (or AGB) and can be estimated with high accuracy when the mean properties describing the microwave interaction with the forest are first determined, and in particular if the phase height is larger than ≈ 5 m. Then, the knowledge of the system noise for a specific forest stand is of less importance. The RMSE for the height of such stands was found to be in the range for Krycklan stands 6–8% and in one case 11%. A computer program is made available for application of IWCM to TanDEM-X data.

The close relation between phase height and the product H95 times the vegetation ratio is discussed and used to illustrate the variability of phase height over the seasons. During winter conditions, the penetration depth is larger and the phase height lower causing a lower sensitivity to stem volume or AGB. Consequently, the TanDEM-X acquisitions during summer days without precipitation and with HoA < 100 m have been found to be most useful.

The TanDEM-X mission has been important for illustrating the potential of single pass and bistatic InSAR, but for TanDEM-X no follow up is planned. One future possibility is a bistatic C-band mission as a complement to ESA:s long term commitment to C-band SAR missions. For C-band as well as X-band, the penetration to ground through dense forest is relatively small, which simplifies the modeling approach and results in phase heights, with a DTM available, close to the tree tops resulting in high accuracy. For this reason, an investigation of the potential of such a mission is investigated based on observations with ERS-1/ERS-2 repeat pass observations. Such observations are sensitive to several decorrelation effects and only in a single case out of nine observations from 1995/1996 are the conditions found to be relevant for analysis of a single pass bistatic mission. A simulation indicated that the sensitivity to stem volume (or AGB) would be similar to that obtained at *X*-band. Such a mission would be valuable also in tropical areas as a complement to BIOMASS, since the sensitivity to forest variables is significantly different due to large differences in operating frequencies.

It should be stressed that the results are based on specific datasets and study sites with related reservations for the generality of the results, but we have seen that forest properties such as stem volume, AGB, forest height and density can be determined with high accuracy from single baseline bistatic TanDEM-X acquisitions, particularly from summer time with HoA < 80 to 100 m. For these results, we have used an available lidar DTM and a height versus stem volume allometry based on NFI observations, and an expression for the area-fill based on lidar measurements.

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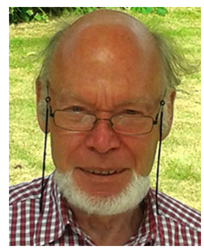

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